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AIRCRAFT PROTECTION
from
THUNDERSTORM ELECTROMAGNETIC EFFECTS — I
(Fin Cap and Radome Antenna System Lightning Protection)

L&T Report 401

M. M. Newman
J. D. Robb

Lightning & Transients Research Institute
Minneapolis, Minnesota

Contract No. AF 33(616)-7828

March, 1962

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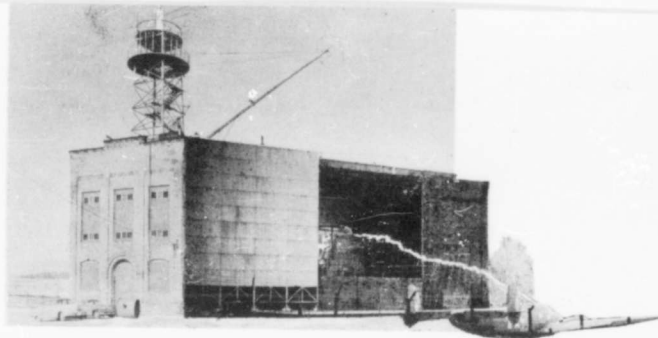
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Communications Laboratory
Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio



**Lightning & Transients Research Laboratory
Lightning and Related Interference Transients**

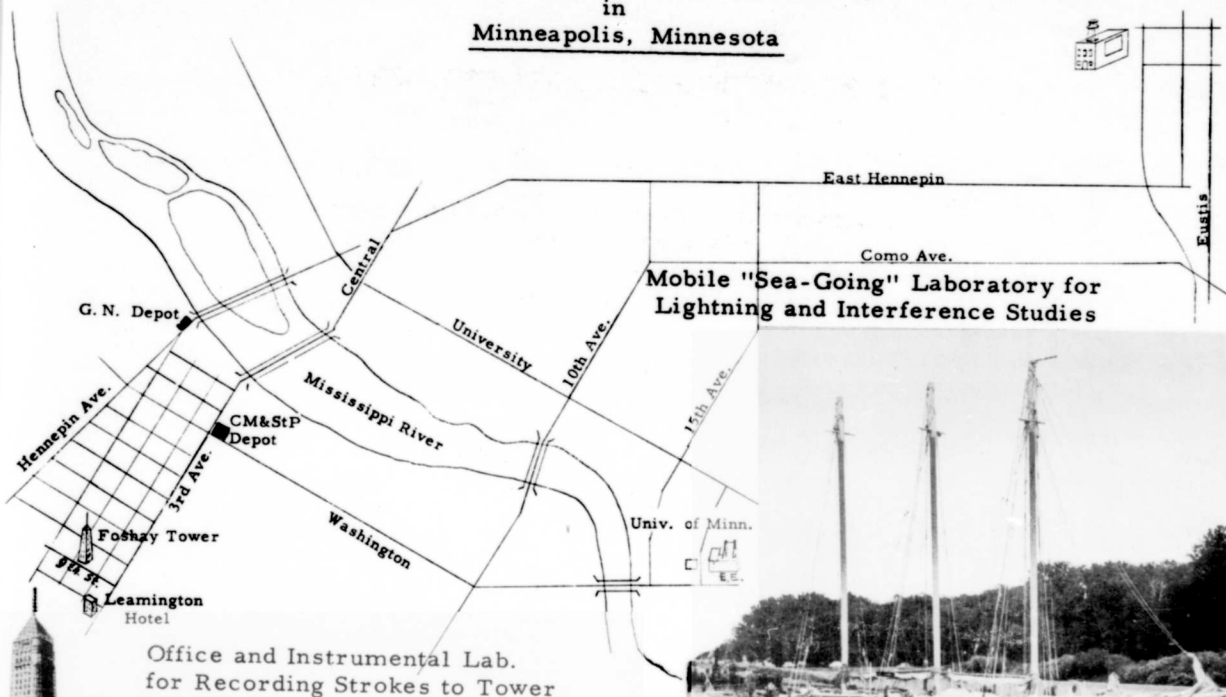
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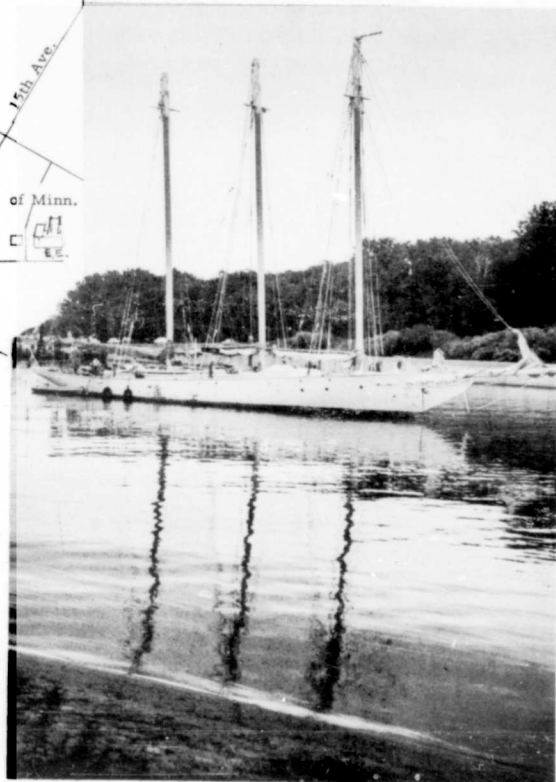
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Mobile Measurements Lab.



FOREWORD

This report was prepared by the Lightning and Transients Research Institute under Contract AF 33(616)-7828 sponsored jointly by the Aeronautical Systems Division, U.S. Air Force and the Navy Department, Bureau of Naval Weapons.

The technical program is administered under the direction of the Communications Laboratory, Aeronautical Systems Division, Mr. H. M. Bartman acting as project chief, and coordinated with the Bureau of Naval Weapons through Mr. V. V. Gunsolley.

Participating scientific and engineering staff taking primary part in this report's researches and preparation included: M. M. Newman and J. D. Robb, also E. H. Yonkers as guest engineer contributed particularly in the antenna lightning arrester development and also in the projected artificial lightning facility expansion planning for full scale lightning environmental research.

This report essentially summarizes in brief publishable form, the presentations given at Wright Field seminar on September 14, 1961 for government personnel, as part of the technical educational phases of this contract. This paper is essentially complete with respect to lightning protection of fin-cap and radome antenna systems. Other areas requiring further development are discussed briefly.

Other brief consultation phases were begun in this quarterly period which will be reported on as completed in later Technical Notes.

ABSTRACT

Aircraft flying in thunderstorms may have radio communications disrupted by corona interference from the strong fields present and structural damage may result from direct lightning strokes.

Although the short duration interference is not usually a major problem, some interference reduction techniques are possible. Thunderstorm lightning to aircraft reports from over 700 incidents are tabulated and, although the data on jets is not yet complete, show the greatest incidence of strikes to occur near 0°C and around 10,000' altitudes with some lightning incidents at 40,000'. Point-of-strike frequencies are also tabulated. Applications of artificial lightning generators and model studies to determine point-of-strike probabilities and reproduce natural lightning in-flight effects are discussed.

Specific topics included are the use of HF lightning arresters to protect the antenna and radio equipment, and the use of graded resistance diverter rods to provide localized point-of-strike control. The development of radome protection is also discussed in detail with particular emphasis on foil strip protection systems and proper use of bonding wires.

The report concludes with a discussion of some of the remaining problems such as the extension of HF protection systems to VHF and UHF antennas, and possible fuel tank and fuel vent hazards from lightning discharges. The feasibility and need for an increased test facility to enable tests on full scale aircraft to be made more effectively is also discussed.

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Aircraft Protection from Thunderstorm Electromagnetic Effects - I

INTRODUCTION

This report essentially summarizes in brief publishable form, the presentations given at the Wright Field seminar on September 14, 1961 for government personnel, as part of the technical educational phases of this contract. This paper is essentially complete with respect to lightning protection of fin-cap and radome antenna systems. Other areas requiring further development are discussed briefly in this paper and will be the subject of more detailed presentations in the later continuation sections.

While faster high altitude jet aircraft usually fly well above most intense thunderstorm activity, their passage up and down through such levels, and occasional schedules at lower altitudes, has resulted in the case of one airline reporting the same one-per-plane-per-year lightning strike average for jet aircraft as obtained in earlier statistical data on propeller aircraft. In general, however, jet aircraft strikes reported average about 1/10 as high a rate as for propeller aircraft; but it is clear that even future higher altitude aircraft, as well as rocket vehicles, will still need to consider lightning effects if departure and re-entry are to be considered on an all-weather operational basis. Greater recent emphasis on all-weather operation for lower altitude aircraft has occasioned greater concern for providing lightning protective improvements on all aircraft including also helicopters.

Protective methods for antenna systems have been discussed in earlier papers, and aside from brief review of other problems yet unsolved, the main emphasis of this paper is on localized stroke diversion control and on various types of radome protective methods.

Note: A slightly modified version as a technical paper, with a few illustrations omitted and the concluding paragraph deferred for closing discussion, was submitted March 17, 1962 for AIEE publication consideration.

Manuscript released by the authors March 1962 for publication as an ASD Documentary Report.

ELECTRO-MAGNETIC EFFECTS OF THUNDERSTORM FIELDS AND NEARBY LIGHTNING

Thunderstorms may introduce a problem of interference with aircraft communications, both by the direct electro-magnetic radiation from nearby lightning discharges and by corona and corona streamers induced on metal surfaces and antennas by intense thunderstorm electric fields. The usual aircraft dischargers, used for quietly bleeding off accumulated static charge in the case of precipitation-static^{1, 2, 3} or exhaust ionization self-charging of the aircraft, are of little use in a thunderstorm, as with external fields, the aircraft may be completely discharged (with zero net charge in between positive and negative cloud charge areas) yet have intense streamers and corona induced by the external field. Some reduction of interference from cross field corona on the antennas can be accomplished with resistively decoupled shielding designs. Electronic gating circuitry^{4, 5} offers some promise of reducing the interference from some of the corona discharges that cannot be eliminated at the source as well as from some of the nearby lightning stroke radiation interference. However, communications interference is not generally a major problem as the aircraft is usually in severe thunderstorm cross fields only for brief periods of time.

Intense cross field gradient induced corona streamers could, aside from causing radio interference, introduce a statistically very small possibility of vapor ignition at fuel system outlets. Aircraft contacted by a branch of the main lightning discharge channel could have intensified streamers as illustrated in the model test shown in Figure 1.

LIGHTNING DISCHARGES THROUGH AIRCRAFT

Natural lightning discharges to aircraft recorded over a number of years have averaged about one strike per aircraft per year for propeller driven aircraft. As shown in Table I, the limited amount of data on pure jet aircraft shows an expected overall reduction in strike probability though individual jet operation reports vary widely, dependent on operational areas, with one airline reporting the same average one/plane/year stroke expectancy as for propeller planes.

As shown in Figure 2, summarized from about 700 strike reports on piston engine aircraft, most strikes occur near 0°C which correlates with thunderstorm electrification theories^{6, 7} that charge separation occurs about the freezing level. Figure 3 indicates that most strikes occur at lower altitudes, but it is probable that the maximum corresponds to the altitude at which most of the recorded piston aircraft flights occurred. One operating record of 14 jet aircraft strikes, as indicated by x's on Figure 3, show a wider spread of altitudes corresponding to the greater range of the jet aircraft operating altitudes.

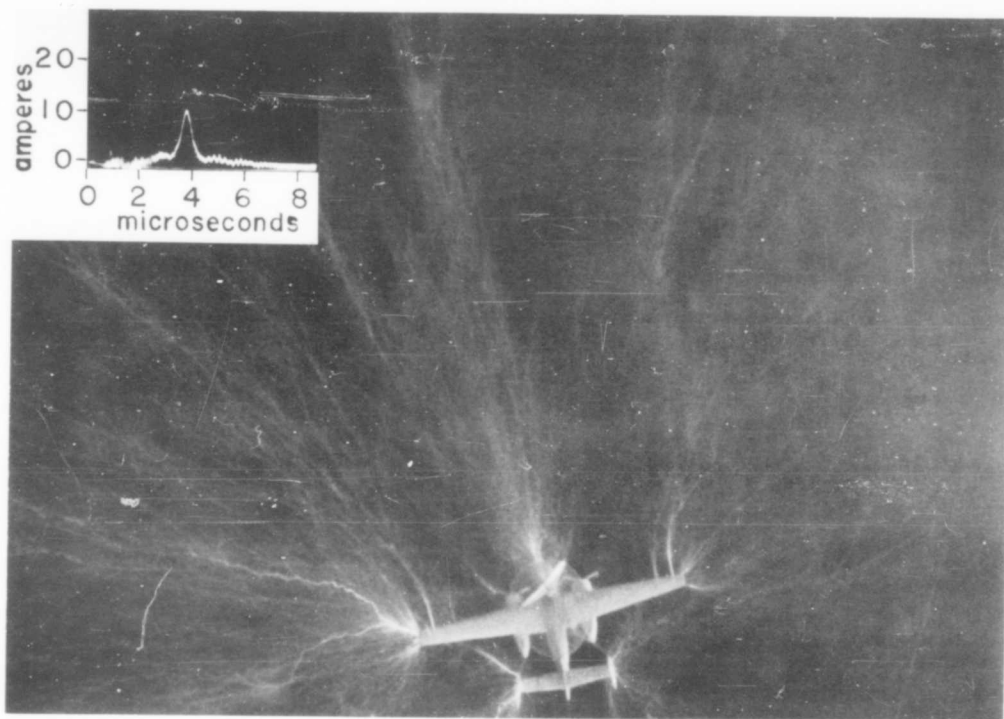


Figure 1. Induced streamers off aircraft extremities illustrated by impulse potential applied to model aircraft.

TABLE I

FREQUENCY OF STRIKES AND DISTRIBUTION OF POINTS STRUCK

(From Strike Reports to LTRI including some Rather Limited Recent Data on Jets from Both American and European Flight Operations.)

	Propeller Driven	Turbo Prop	Pure Jet
No. of strikes analyzed	808	109	41
Approx. hours flown	2, 000, 000	415, 000	427, 000
Incidence of strikes to hours flown	1/2500	1/3800	1/10, 400
% of Strokes to Points Below:			
Vertical fin	14%	11%	17%
Wingtip	19%	29%	19%
Nose	9%	10%	16%
Fuselage	2%	11%	15%
Antennas	29%	18%	16%
Elevators	12%	12%	12%
Jet pods or props	5%	1%	-
Tail cone	1%	1%	-
Miscellaneous	9%	7%	5%

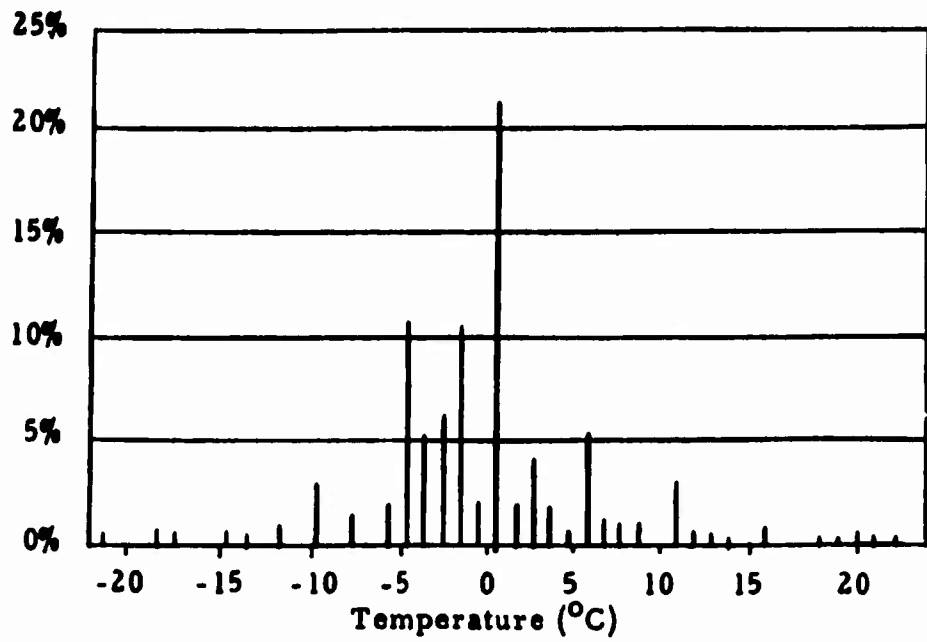


Figure 2. Lightning to aircraft as function of temperature.

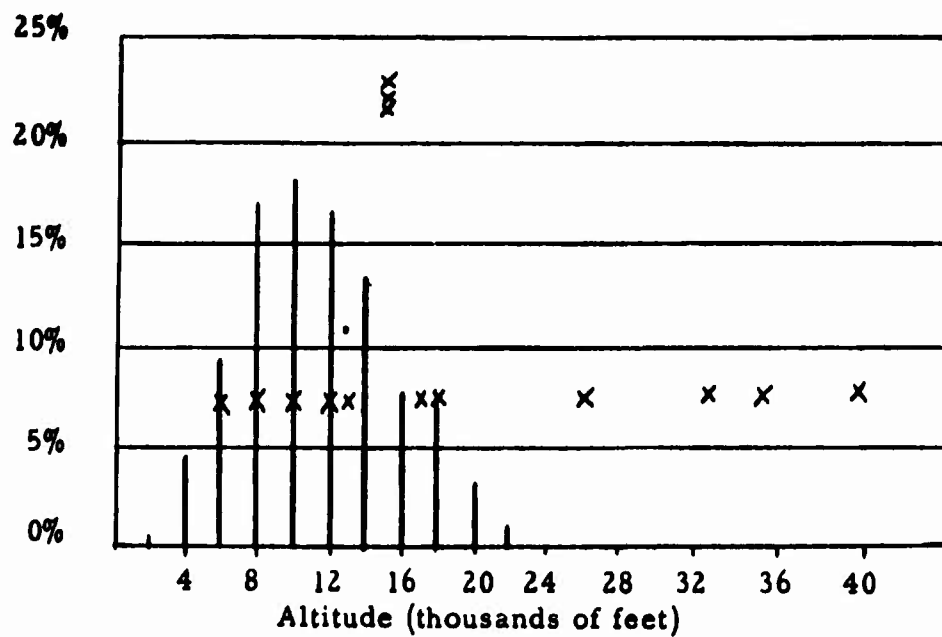


Figure 3. Lightning strokes to aircraft as function of altitude.

Lightning involves potentials of the order of 10^8 volts, currents sometimes exceeding 100,000 amperes, and charge transfers exceeding 200 coulombs, with tremendous total energies. Little of this energy can, however, be developed in the low resistance all metal aircraft skin which provides excellent shielding of the interior. Although lightning has not statistically been considered a major hazard, it can cause expensive major damage to plastic sections such as radomes, fin caps, radio antennas, radio equipment and minor damage to flap and control surfaces and hinge bearings, in addition to producing holes in thin metal skins. A distribution of the lightning damage recorded on propeller driven aircraft, with limited data on jet aircraft, is also presented in Table I. A few records indicated severe enough damage to constitute a potential structural hazard. With faster and larger aircraft, attention has also been given in recent investigations^{8, 9} to potential hazards to fuel systems which might be introduced by new fuels and methods of aircraft construction.

Flight damage to aircraft recorded over a period of fifteen years has indicated stroke intensities far exceeding those specified by the power industry for testing transmission line equipment. For example, the standard 10 x 20 microsecond, 65,000 ampere test current wave, (10 microseconds to a 65,000 ampere crest and 20 microseconds to half crest value) merely roughens thin aircraft aluminum skin while natural lightning strikes, sometimes with long duration low currents with total charge transfer probably as high as 600 coulombs, produce holes up to 4 inches in diameter. Another example of lightning discharge current magnitudes is illustrated in the case of an aircraft on which a radome was blown off. An artificial discharge with many times the current and energy of the 65,000 ampere standard test wave was required to reproduce this damage in the laboratory. Representative test current components which have been used to reproduce aircraft lightning damage are illustrated in Figure 4.

When an aircraft receives actual damage, such as holes burned in the skin, it has intercepted a cloud to cloud or cloud to ground lightning discharge and not a so-called static discharge which implies a discharge terminating on the aircraft. As the aircraft capacity is small, of the order of a few thousand micromicrofarads, it can be shown that even at large potentials, insufficient energy is stored to produce holes in metal skins, and therefore, any visible pitting or denting damage must be caused by a lightning discharge which has passed through the aircraft.

The great variance in lightning energies as reflected in damage reports is caused primarily by the variations in resistance and volatility of the discharge path, although large variations in the stroke magnitudes are also indicated in flight damage reports. The tremendous overall stroke path potentials produce in effect a constant current regardless of the localized path resistance; the energy dissipated in aircraft components is therefore a function of the resistance of the localized current path through

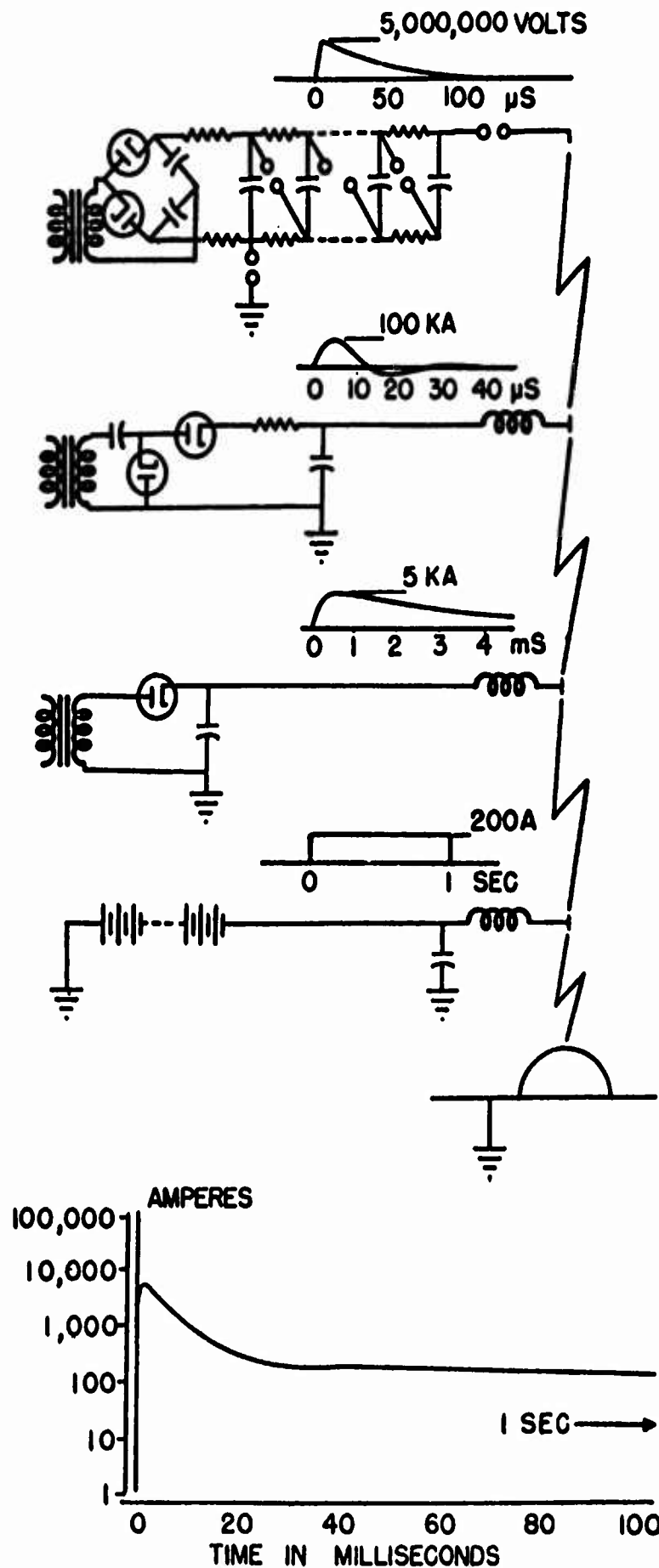


Figure 4. Artificial lightning generator with multiple current component sections, and resultant composite output current waveform.

the aircraft and the greater the path resistance, the greater the energy developed. For example, typical lightning discharges can be carried by conductors equivalent to that required by the present military bonding specification with only slight heating, but a discharge through a poor conductor could produce high temperatures and, if volatile materials are present, high gas pressures to produce explosive effects. The military bonding specification recommends #12 equivalents (6475 circular mils of stranded copper) on the basis that at least two bonds will carry the lightning currents in a stroke to a properly bonded aircraft. As the critical factors are the geometrical configuration and connector types, reliance should not be placed entirely on wire size and for important applications, high current tests are recommended. With suitable geometries and connector types, a single equivalent conductor size would be at least #8, although in cases where protection is required for the more severe discharges for which there has been some recent evidence or for critical applications, larger sizes up to #4 might be required.

Special high energy artificial lightning discharge facilities have been set up to reproduce typical recorded flight damage. Superposed multiple components had been evolved to reproduce the magnetic forces, blast effects and metal erosion of natural lightning discharges. Standard test current waves have consequently been established in a military specification requiring equivalent components of 100,000 amperes crest 5×10 μ sec wave shape, followed by an intermediate 25 coulomb 5000 ampere crest pulse of 10 millisecond duration and a 200 coulomb 200 ampere pulse duration of one second, as illustrated in Figure 4. This represents a typical severe lightning strike but recent evidence has indicated strokes of much greater magnitude and consequently much higher energy artificial test discharges should be used where serious hazards might result from failure of a protection system.

To determine the areas on a specific aircraft which have the greatest probability of being struck, model studies have been made using several million volt discharges as illustrated for one of the discharge orientations in Figure 5. The model studies are not expected to give highly accurate measurements of the exact distribution of points on the aircraft which may be struck but rather indicate the areas of possible problems as these cannot necessarily be anticipated from a review of similar aircraft flight damage history. As shown in Figure 5, model studies of the particular aircraft indicated a susceptibility of the VHF antennas to lightning strokes and subsequent high energy tests of the full size VHF antenna showed that the antenna would be completely destroyed by a typical lightning discharge as illustrated in Figure 6. Protection principles for various antennas have been developed as discussed in the following section.



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Figure 5. Two million volt discharge to model aircraft illustrates VHF antenna susceptibility to lightning stroke.

389-F

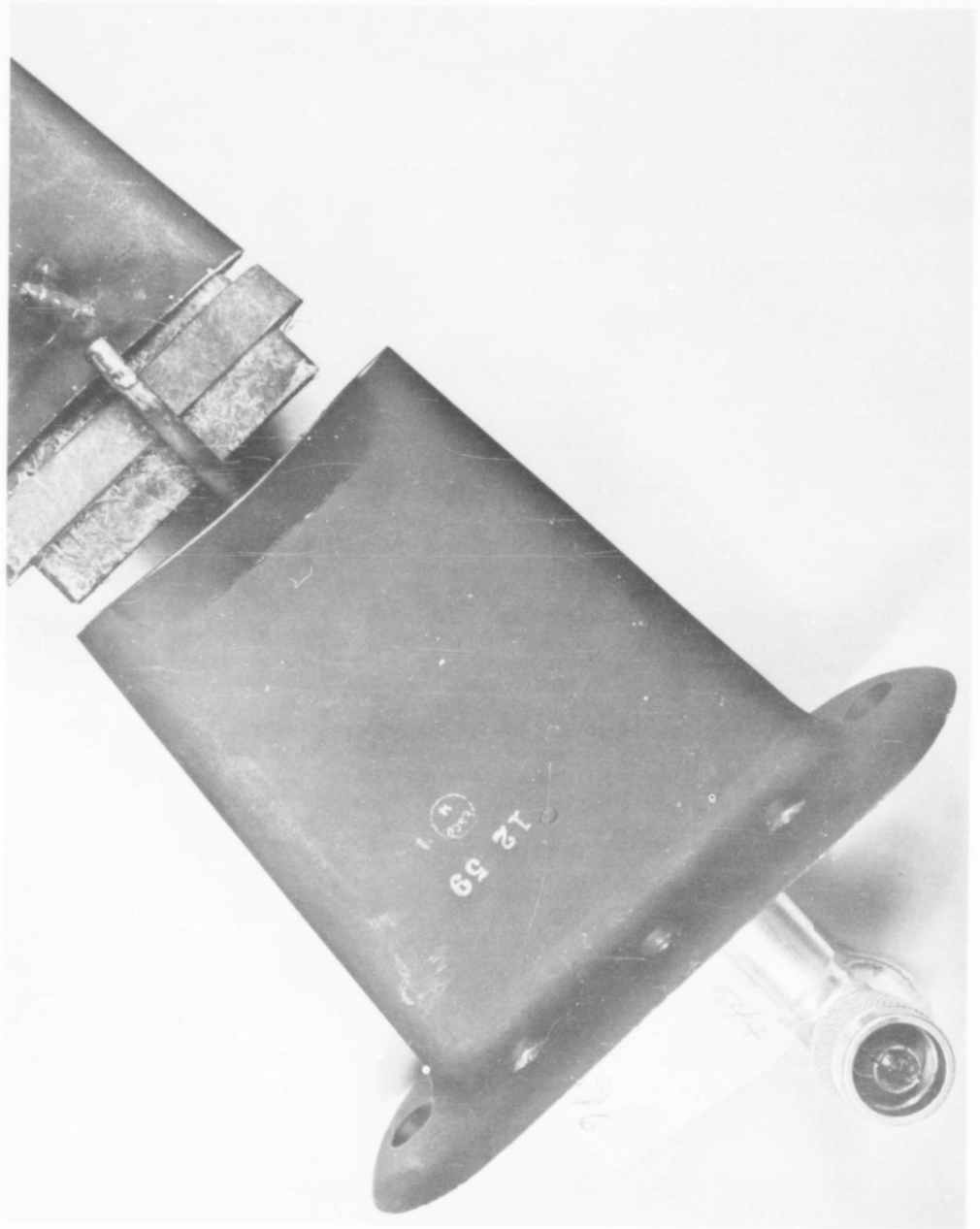


Figure 6. VHF antenna damaged by high current artificial lightning discharge.

LIGHTNING PROTECTION FOR ANTENNAS AND RADIO EQUIPMENT

Although the all metal skin provides excellent shielding of the aircraft interior from lightning discharge energies, points of possible stroke entry such as antenna lead-in conductors must be protected. HF aircraft lightning arresters for protection of radio equipment in the 2 to 20 mc range as discussed in several previous papers^{10, 11} have been developed to bypass lightning discharges on the antenna lead safely to the airframe by use of series blocking capacitors and bypass shunt gaps as illustrated in Figure 7. The series capacitor passes the radio frequency energy with little loss but the lightning stroke energy that is passed to the radio equipment is limited to the capacitor charging energy of generally less than one joule. The lightning current is bypassed by the shunt gap to the airframe.

The most important application of HF lightning arresters is for flush antennas. Lightning discharges to these antennas without protection could flash inside the isolation gap and vaporize plastic resins to produce seriously high gas pressures, and in some cases open arcs might constitute an ignition hazard in event of nearby fuel vapor. An arrester safely contains the lightning arc while bypassing the discharge currents to the airframe and this function is often more important than just protection of the radio equipment.

It should be emphasized that use of a lightning arrester does not in itself provide protection of a flush antenna isolation gap. It has been found that in some cases parallel components across the gap, such as VHF isolation units and navigation light isolation transformers, have had lower impulse breakdown voltages than the rated arrester gap voltage and have been damaged by lightning discharges. Also, plastic sections of aircraft isolation gaps have been blown off aircraft and in other cases severe structural damage has been done with improper fin cap arrester installations. Once the lightning discharge passes through a weak component, it may explode the component without ever firing the arrester protection gap. Thus all other components across an isolation gap, including the isolation gap structure, must have an impulse breakdown voltage at the reduced pressure encountered at altitude, which is considerably higher than the rated arrester gap voltage to avoid arcs or explosions inside the sections and system checks are essential.

As illustrated in Figure 6, many VHF antennas are highly susceptible to lightning damage. LTRI records of lightning damage to commercial aircraft show as much damage to the VHF radio equipment as to HF but to date few designs have incorporated lightning protection. Arresters can be provided for existing VHF antennas, to protect the associated radio equipment but new antennas can be designed to be lightning stroke resistant

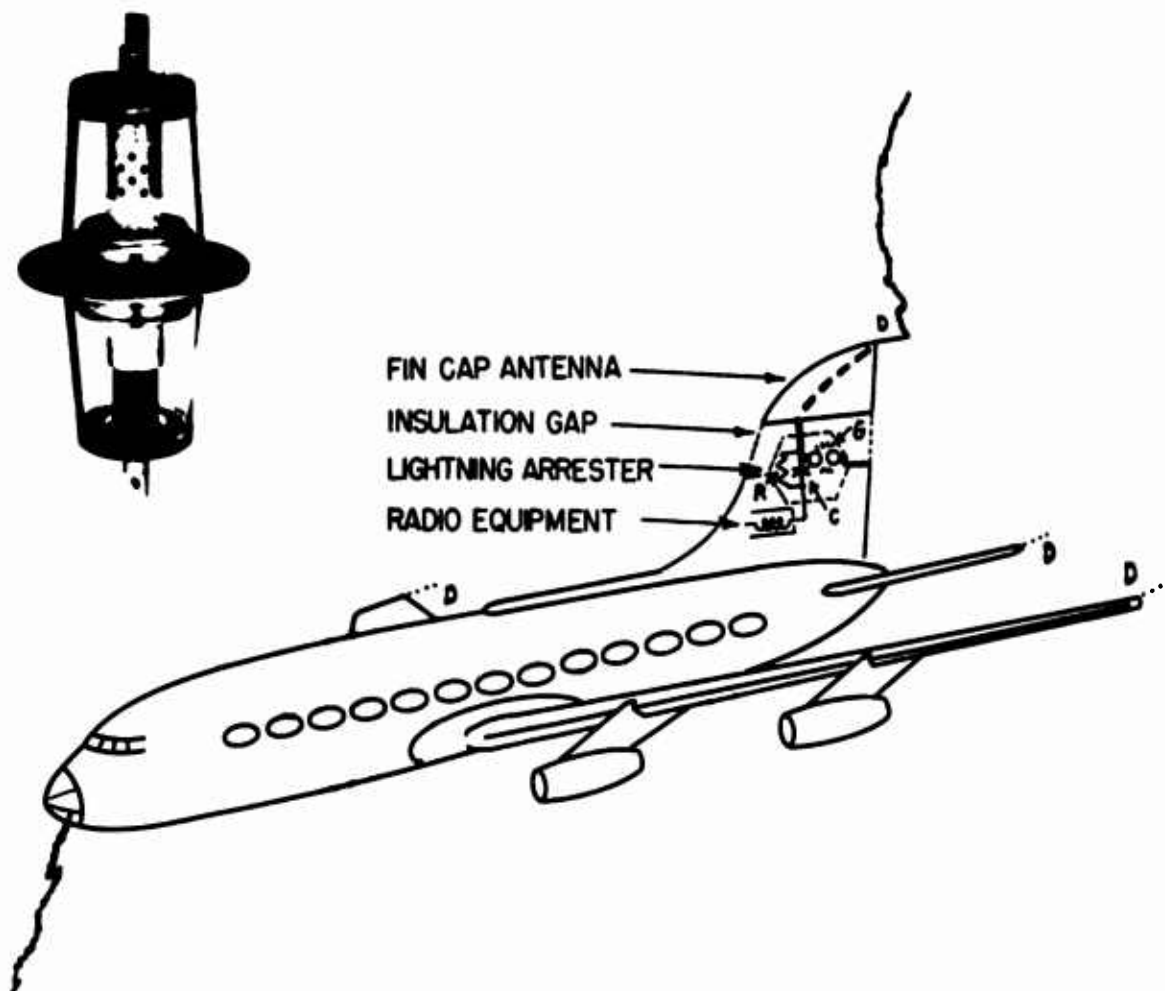


Figure 7. Diagram illustrates arrester antenna system protection of fin cap.

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#1805

and also to protect the associated radio equipment by use of grounded designs or VHF capacitor spark gap techniques. Such techniques with adequate grounding to the aircraft skin are important to prevent penetration of the stroke energies into the aircraft interior.

DIVERTER ROD LOCALIZED CONTROL OF POINTS OF LIGHTNING STRIKE

Realizing that little can be done to prevent discharges from striking the aircraft, LTRI had developed a graded resistance lightning diverter rod for controlling somewhat the specific localized point at which lightning might strike. The graded resistance diverter rods were constructed to locally divert strokes to points designed to carry stroke currents without introducing excessive radio noise. This was accomplished by use of an insulated fiberglass rod coated with a resistance paint and consisting of three to six sections, each section with a higher resistance than the preceding, beginning with the lower resistance portion nearest the aircraft. An example is shown in Figure 8.

Because of the successive concentration of potential over the highest unflashed portion of the graded resistance, the discharge, initially attracted by the diverter tip localized streamering, is guided along the diverter rod. Strokes may thus be guided past metallic conductors extending into the space near the diverter. This principle has been effectively demonstrated in the laboratory in guiding strokes over the outside of an insulated aircraft fin containing a VHF antenna. It is of importance to assure that the diverter rod base is designed to carry the severe stroke currents without damage to the skin or airframe at the attachment point.

The major advantage of the graded resistance system over metal rods is quiet electrical discharge while under the influence of electric fields produced either by precipitation charging of the aircraft or the presence of the aircraft in thunderstorm regions. The locations on an aircraft where lightning strikes are most probable (the high gradient points) are also the points which produce the most radio noise from corona discharge currents and therefore metal rods are very noisy and not generally practical. The graded resistance diverters, in addition to acting as lightning rods, also assist in discharging the aircraft under precipitation-static conditions. A typical application where diverters may be used is in the protection of vulnerable areas such as the rudder section shown in Figure 9. The guiding action of the diverter is illustrated by the right angle turn of the discharge, and the principles are also applicable to advantage in radome protection.

Antierosion
coating over
entire exterior
of whip

Length
18 inches to
36 inches

Thickness
5/32" at tip
to 5/16" at base

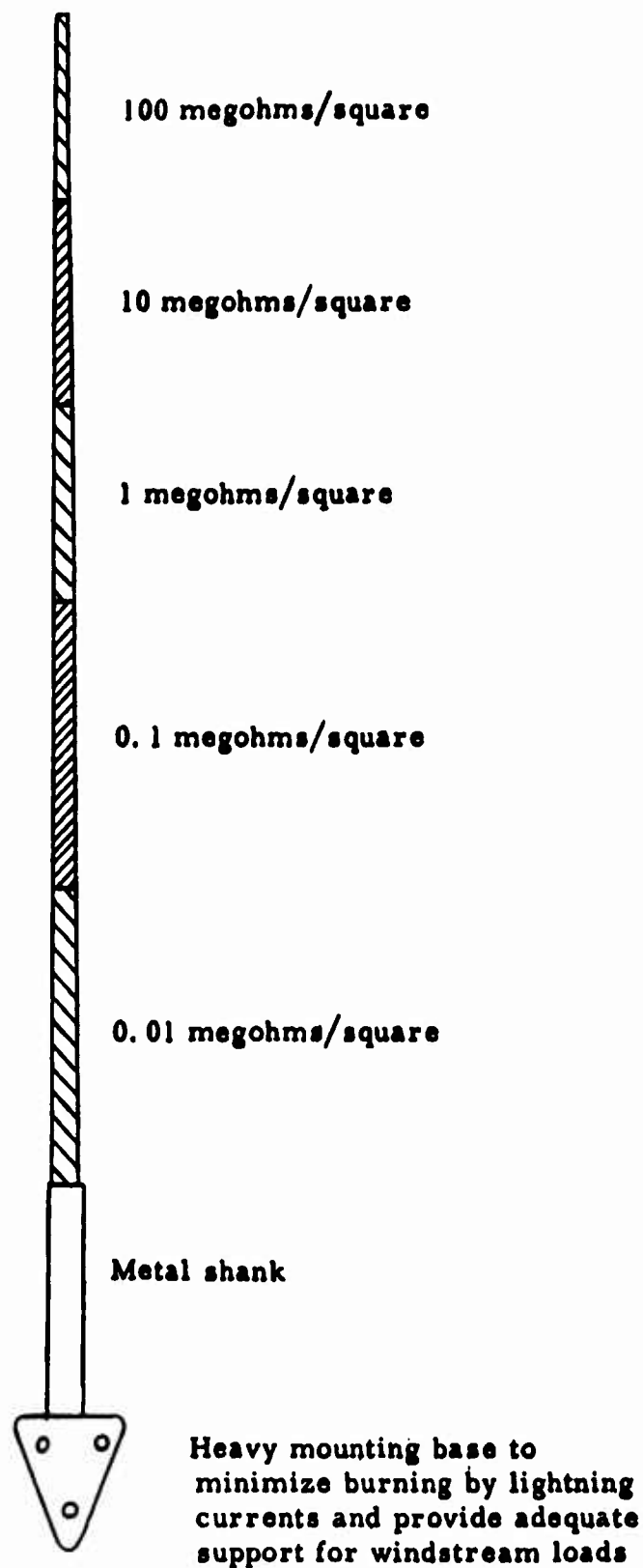


Figure 8. Graded resistance fiberglass lightning diverter-discharger schematic.

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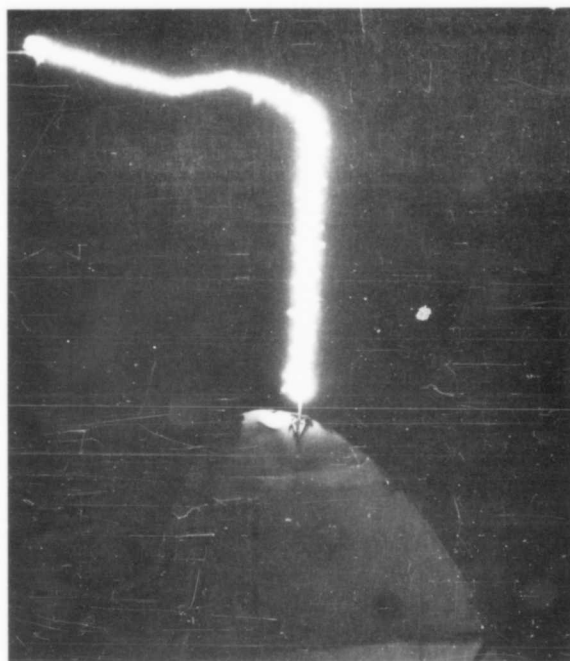
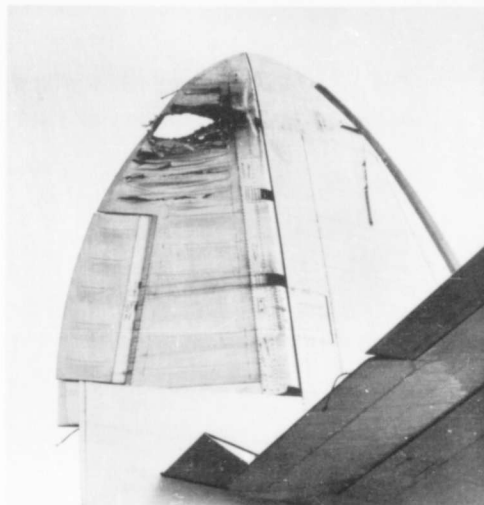


Figure 9. Illustration of graded resistance diverter guiding discharge in protecting aircraft rudder section.

DEVELOPMENT OF RADOME LIGHTNING PROTECTION

An illustration of the early use of external metallic conductors for protection of plastic enclosures on aircraft is shown in Figure 10. A solid copper bar was placed over the plastic canopy of an F-15 photo aircraft used for intercepting and recording lightning discharges as part of the Air Force "Thunderstorm" project. As this was the only aircraft in the "Thunderstorm" group which had a clear plastic canopy rather than a metal cabin roof and as it was instrumented specifically to intercept and record lightning strokes, it seemed advisable to provide some type of protection. The solid copper bar was installed over the canopy and artificial lightning discharges, as shown in the photograph of Figure 10, were fired with the pilot and a passenger under the canopy to provide a realistic test. Only a slight shock comparable to the static shock obtained from a light fixture was noted by the two occupants from electrostatic field penetration beyond the top diverter bar struck by an artificial lightning discharge of several million volts.

As the use of radomes became more common, lightning protection was provided in many cases by solid metallic conductors as shown in Figure 11, arranged in a suitable pattern so as to provide minimum interference with the radar operation and provide maximum protection for withstanding lightning discharges. Also aluminum foil strips were evaluated for the same purpose using a variety of foils and a wide range of artificial lightning discharge currents. Figure 12 shows the application of the foil system to a plastic enclosure, as demonstrated and discussed in the LTRI 1948 Symposium on "Lightning Hazards to Aircraft." This system has since been adapted for use on some modern transport radomes and has been successful in providing protection. The foil conductors must have a certain minimum mechanical strength, however, as any breakage of the metallic conductors results in isolated sections radiating as VHF antennas at their equivalent wave length by excitation from sparkover to adjacent sections under thunderstorm fields or precipitation-static conditions. Conducting coatings are generally recommended for use over the entire radome surface to reduce precipitation charge streamering and possible static puncture as well as to greatly reduce the electrical gradient and tendency for corona discharge from protection strips.

Another method of protecting radomes which enclose antennas not compatible with metallic protection conductors is the use of nearby diverter rods of the graded resistance type previously discussed. Also a graded resistance coating may be applied directly over the radome surface. The graded resistance has the advantage of providing lightning protection while introducing minimum interference to the enclosed antennas. The disadvantage of the graded resistance system on the radome surface is that a much higher radome dielectric strength is required to resist lightning stroke puncture.

374-A



Figure 10. Artificial lightning discharge to canopy with heavy protecting diverter bar.

387-B

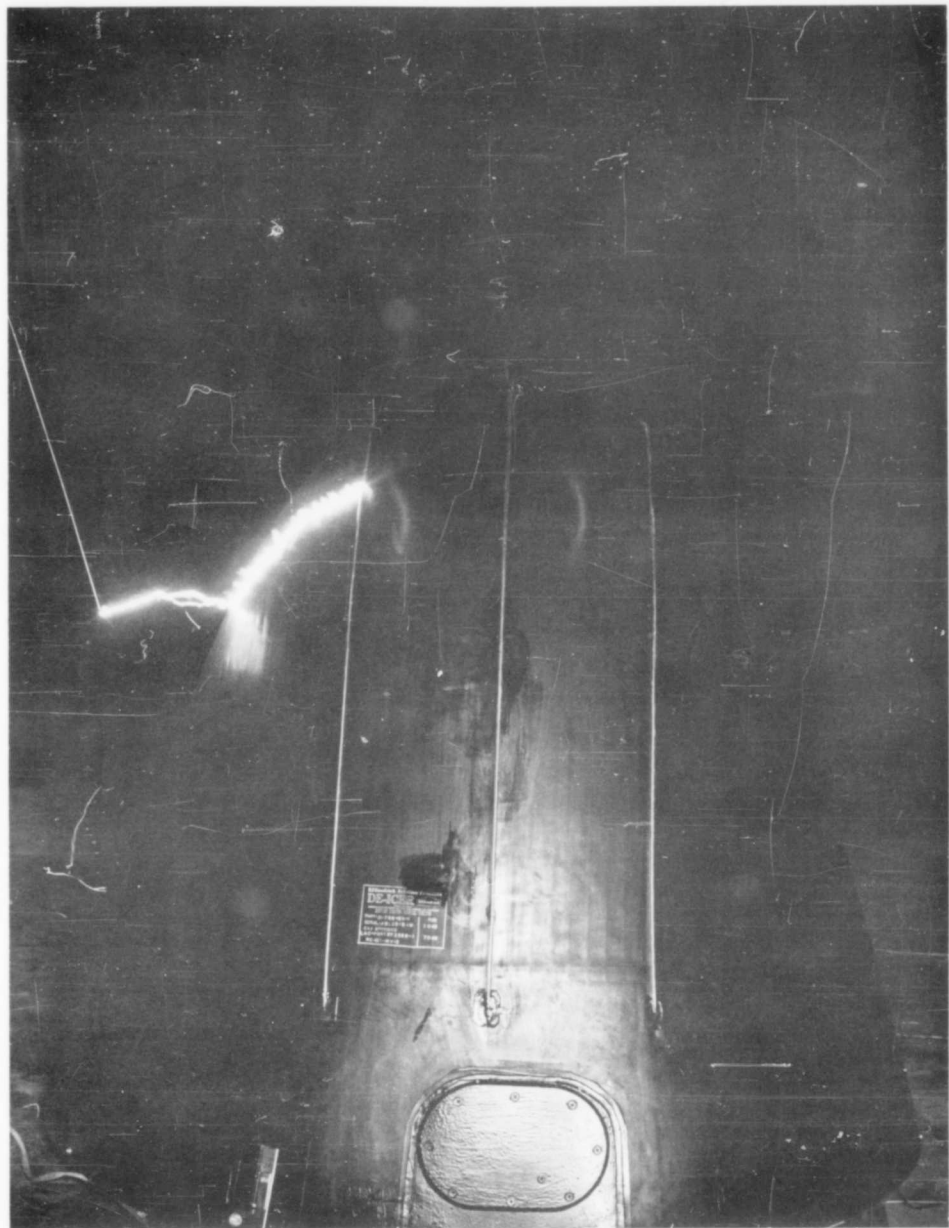


Figure 11. Lightning protective diverter wires on radome with heavy enough cross section to withstand moderate discharges.

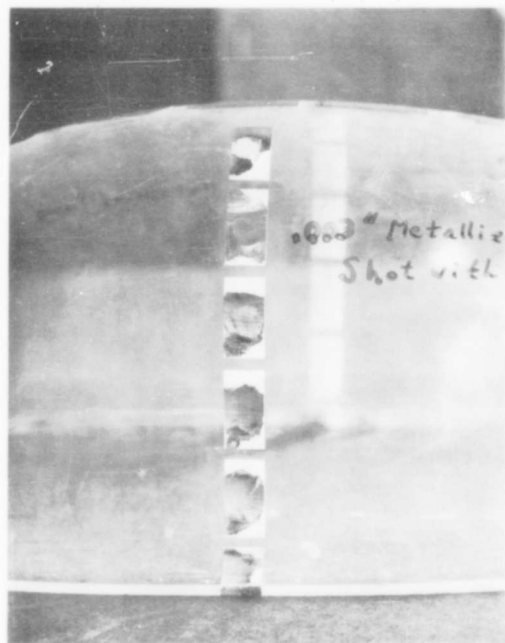
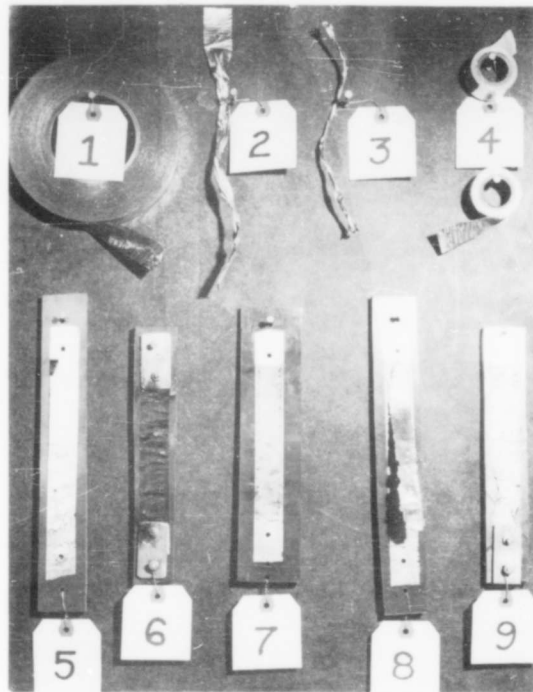


Figure 12. High current discharge effect on gapped metal-foil protection strips.

A combination foil strip and diverter system, which has been effectively utilized for protection of sections of radomes covering critical antennas, used partial discharge guiding action of surface flash-over facilitating characteristics of aluminum paint with its isolated conducting flakes, as illustrated in Figure 13. The aluminum paint system by itself requires higher radome dielectric strengths than do the conventional metallic foil conductors; however, its effective use for protection of critical sections of radomes, using metallic foil strips in less critical sections, has been successfully demonstrated. Attenuation of the aluminum coating at radar frequencies has been found to be remarkably low. Up to 8 coats have been found to introduce a loss of only a few percent.

Solid laminate radomes such as used on fighter aircraft have considerably higher dielectric strengths than the normal sandwich radomes; however, for long radomes which have large surface flashover lengths, puncture is still possible even with fiberglass sections as thick as 5/8". Puncture of such a radome is illustrated in Figure 14 and protection of this radome should preferably be provided by external conductors.

In the case of the radome shown in Figure 14, an internal bonding wire was substituted in production as an apparent equivalent to the tested external system, but the particular unchecked internal system failed in the case of a natural lightning strike. Later laboratory tests immediately disclosed that in the production models a 90 degree bend in the wire for easy attachment to the aluminum frame at the rear of the radome had resulted in sufficient magnetic forces from high stroke currents to blow the wire away from the connector. The stroke currents were then carried through a glycol de-icer line which vaporized to produce gas forces sufficient to blow the radome off the front of the aircraft. This effectively illustrates the definite need for checking of final manufactured production systems with artificial lightning discharge currents in view of the severe effects which can be produced by new unforeseen factors that may result from what may appear to be relatively minor manufacturing changes.

Typical radome damage is illustrated in Figure 15 for a thick radome honeycomb panel. The damage was actually produced by an artificial lightning discharge but is similar to that produced by natural lightning. In some cases the natural lightning damage may be considerably more extensive when amplified by the aerodynamic loading in flight.

An illustration of full scale checking of large aircraft lightning protective designs, is shown in Figure 16. The LTRI research schooner¹² Azara was used to check an airplane with a specially large upper radome to determine an optimum lightning protection system. Such full scale tests of a final manufactured radome configuration are particularly recommended where the radome damage could result in loss of the aircraft as in the case of the jet aircraft radome shown in Figure 14 or the very

387-D

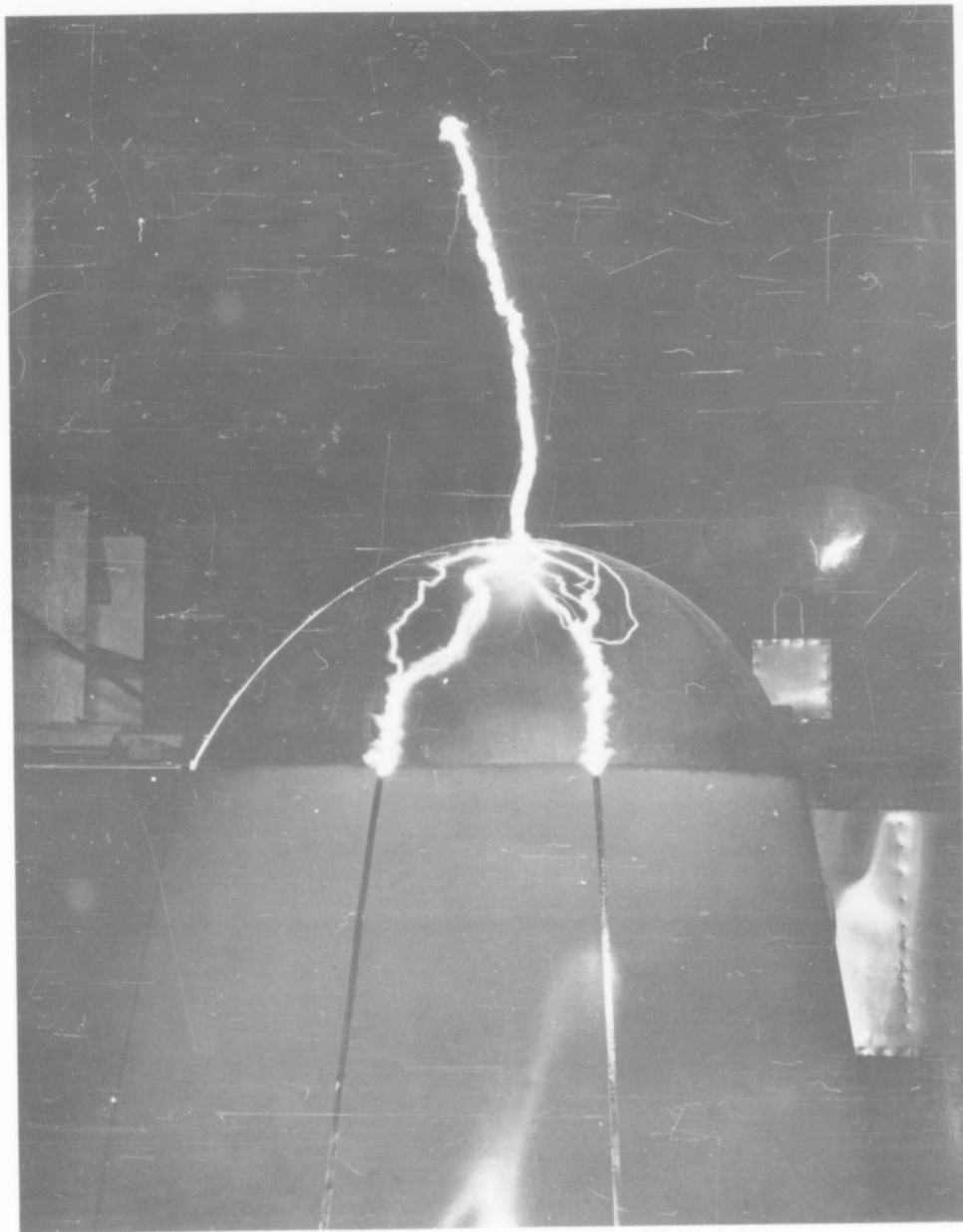


Figure 13. Discharge to special radome with aluminum paint used for lightning stroke diversion to foil strips below.

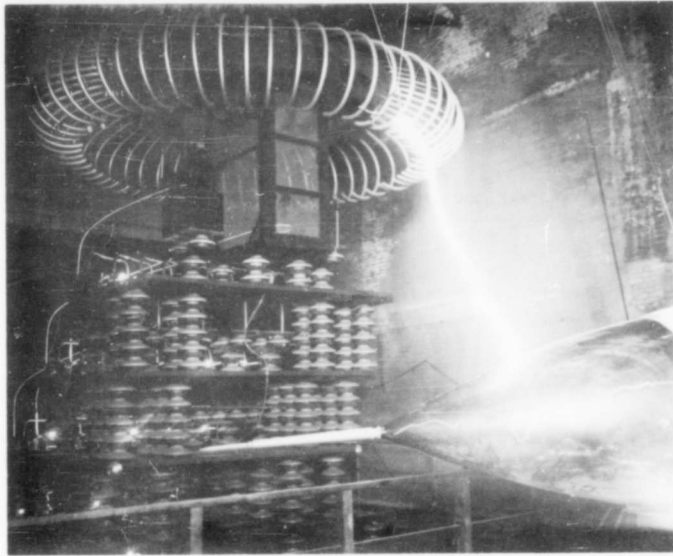
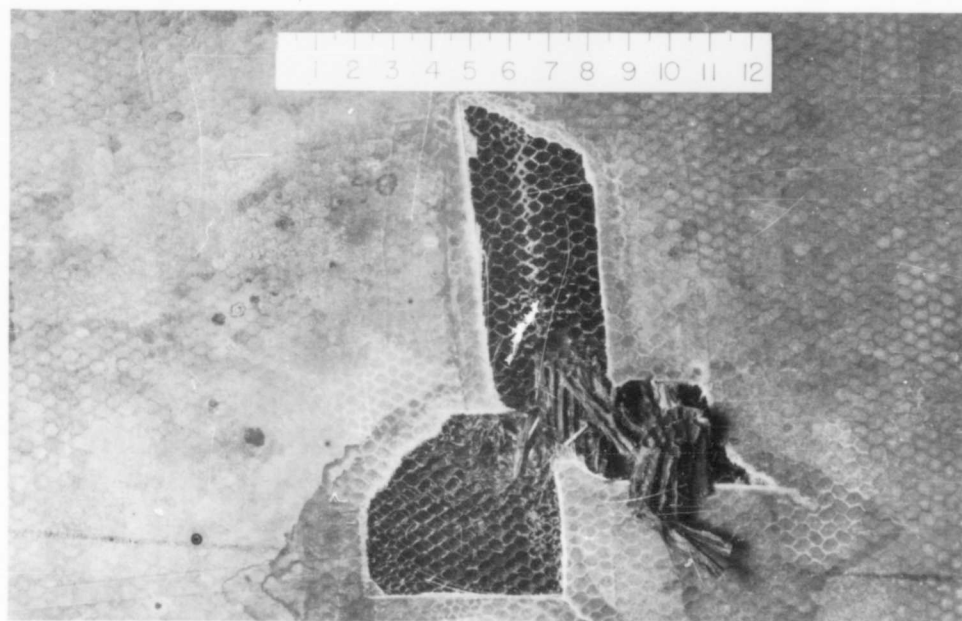
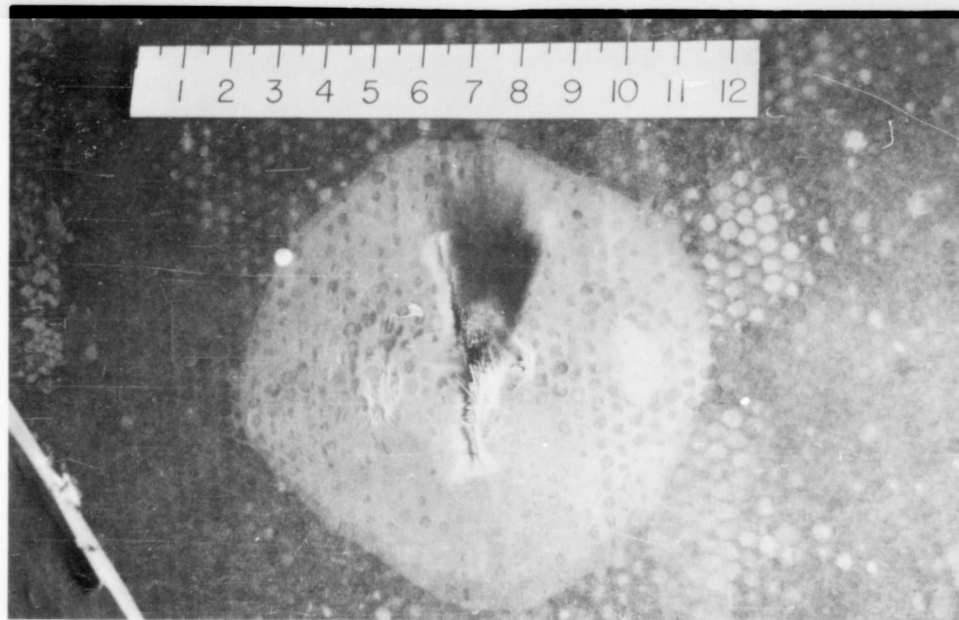


Figure 14. Laboratory lightning discharge through thick radome to wires inside.



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Figure 15. Damage to radome honeycomb section from high current discharge.



Figure 16. Full scale test of large radome using LTRI schooner borne two million volt lightning generator.

large radome shown in Figure 16. Actually the voltage limitations of the mobile installation to 2 million required separate model tests to determine the areas to be probed in the full scale tests. It would seem worthwhile to build up a higher voltage and current facility so that known lightning characteristics can be more adequately reproduced in full scale checks of the entire aircraft. It has been determined to be entirely possible to build up a larger mobile sea-going generator version (similar to unit described in reference 12), of 20 million crest voltage output capable of discharging to test aircraft in actual flight over the facility.

REVIEW OF PROTECTION POSSIBILITIES AND SOME REMAINING PROBLEMS

The general problems involving aircraft and thunderstorm electromagnetic effects, primarily relate to lightning discharges which may do direct damage, and to related radio interference which may introduce a serious loss of communications in thunderstorm areas.

A brief summary is given below of various areas of progress accomplished in lightning protective improvements, with comments on the state-of-the-art to date and possibly needed further research and development.

1. Aircraft HF antenna system protection from directly intercepted discharges is essentially solved with lightning arrester designs already evolved. Various arresters are now available commercially, but it is to be emphasized that complete system checks are essential for individual aircraft designs.
2. Extension of protective techniques to special UHF and VHF mast antennas and various receiving antenna systems is now feasible within guide lines and quality control under specifications and tests adopted as military standards.
3. Radome protection has been evolved with diverter strip systems of various kinds, and production designs which had been laboratory checked have worked out satisfactorily under natural lightning conditions.
4. Further development work will be needed on special problems with new radome designs where dimensions, materials, and internal gradients from different antennas, etc., may be different enough to introduce new factors.
5. Individual laboratory lightning tests for new design prototypes are essential to check designs based on general principles. There have been

many examples where apparently unimportant seeming production modifications have proved unsuitable. With so many interrelated factors, an artificial lightning check of the final production design as an integrated part of the overall system is considered important and preferable to waiting for field experience statistics.

6. Fuel system ignition by lightning discharge currents presents a major area in which the state-of-the-art is uncertain, and further researches are in progress under government and industry support to determine the degree to which hazards may exist; and a parallel industry cooperative program is developing interim protective approaches to reduce the potential hazards even though their actual extent is statistically uncertain.

7. Laboratory lightning effect studies have permitted, by comparison with aircraft lightning damage, a fair determination of the lightning characteristics with corresponding success in evolving protective methods--with a conclusion, however, that more data is needed on the lightning channel, as for instance with respect to pressure waves possibly detonating fuel mixtures or adding structural stress to turbine vanes. Also, while partial work with models has been effective, a planned increase of test facility for full scale tests would seem very worthwhile.

In concluding discussion, it would seem worthwhile to continue the gathering of flight strike data following the earlier work of L. P. Harrison¹³, with the later simplified one page LTRI questionnaire¹⁰ further modified as illustrated in Figure 17. Also continued analyses of lightning strike damage^{14, 15, 16} in comparison with laboratory reproduced lightning effects will usefully add to our knowledge as to the magnitude and characteristics of lightning currents to be expected through aircraft. Recent records indicated some aircraft intercepted lightning discharges considerably exceeding prior expectancies, with evidence of currents of over 200,000 amperes and charge transfers of over 600 coulombs; and therefore consideration might be given to revising standards for protective equipment specifications to take into account the more severe discharges. Extension of artificial lightning facilities to reproduce the more severe discharges and more closely approximate the natural lightning environment is technically feasible, as illustrated in Figure 18, even to the extent of directly checking some phases of lightning protection development on aircraft under actual flight conditions.

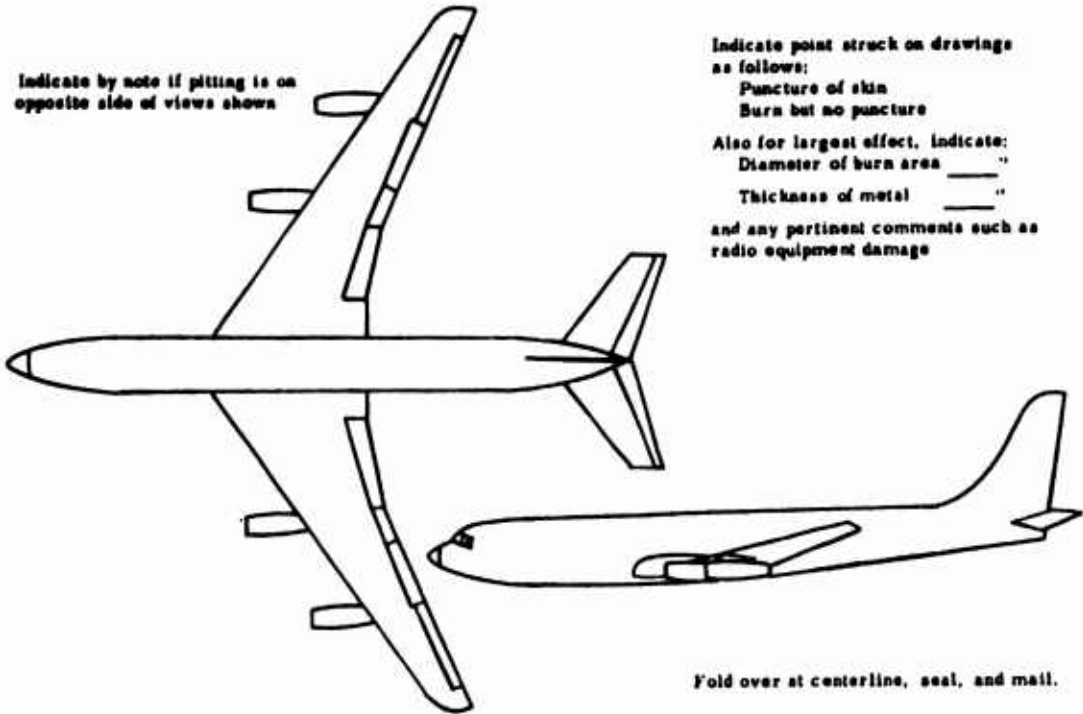
ACKNOWLEDGEMENTS

Research support of the U.S. Air Force, Navy and NASA is gratefully acknowledged, with particular appreciation of technical cooperation of H.M. Bartman and V. V. Gunsolley. Joslyn Mfg. & Supply Company has cooperated in arrester development, and Dayton Aircraft Products Co. has assisted in diverter-discharger development. An informal industry cooperative research program supported by Boeing, Convair, Douglas, Lockheed and North American has also greatly advanced the lightning protective developments discussed in this paper.

Airline data recording cooperation, particularly by American and Pan Am. in the U.S.A. and BOAC and KLM abroad, and discussions with E. Lloyd of the British Air Registration Board and with visiting pilots of the USAF and RCAF, have also been very useful with respect to evaluating thunderstorm flight operations experience.

Parts damaged by lightning														
Instructions: Mark x in proper box in margin.														
Lightning & Transients Research Institute Minneapolis, Minnesota														
Aircraft Questionnaire on Lightning and Atmospheric Effects														
<div style="display: flex; justify-content: space-between;"> organization _____ altitude _____ air temp. _____ °C </div>														
<div style="display: flex; justify-content: space-between;"> Date _____ time _____ location _____ </div>														
<div style="display: flex; justify-content: space-between;"> Airspeed _____ Type of Aircraft _____ </div>														
Meteorological Environment														
<div style="display: flex; justify-content: space-between;"> Clouds _____ precipitation _____ turbulence _____ lightning in vicinity _____ </div>														
<div style="display: flex; justify-content: space-between;"> storm _____ light _____ moderate _____ heavy _____ some _____ cloud to ground _____ cloud to cloud _____ </div>														
Radio interference														
<div style="display: flex; justify-content: space-between;"> lightning static _____ precipitation static _____ slowly varying _____ fast varying _____ ADF interference _____ HF interference _____ VHF-VLF interference _____ </div>														

Indicate by note if pitting is on opposite side of views shown



Indicate point struck on drawings as follows:
Puncture of skin
Burn but no puncture

Also for largest effect, indicate:
Diameter of burn area _____"
Thickness of metal _____"

and any pertinent comments such as radio equipment damage

Fold over at centerline, seal, and mail.

Figure 17. Lightning questionnaire modification for simplified data analysis, with individualized aircraft sketch on which strike points are to be indicated. Page to be folded along centerline, sealed and returned for statistical tabulations.

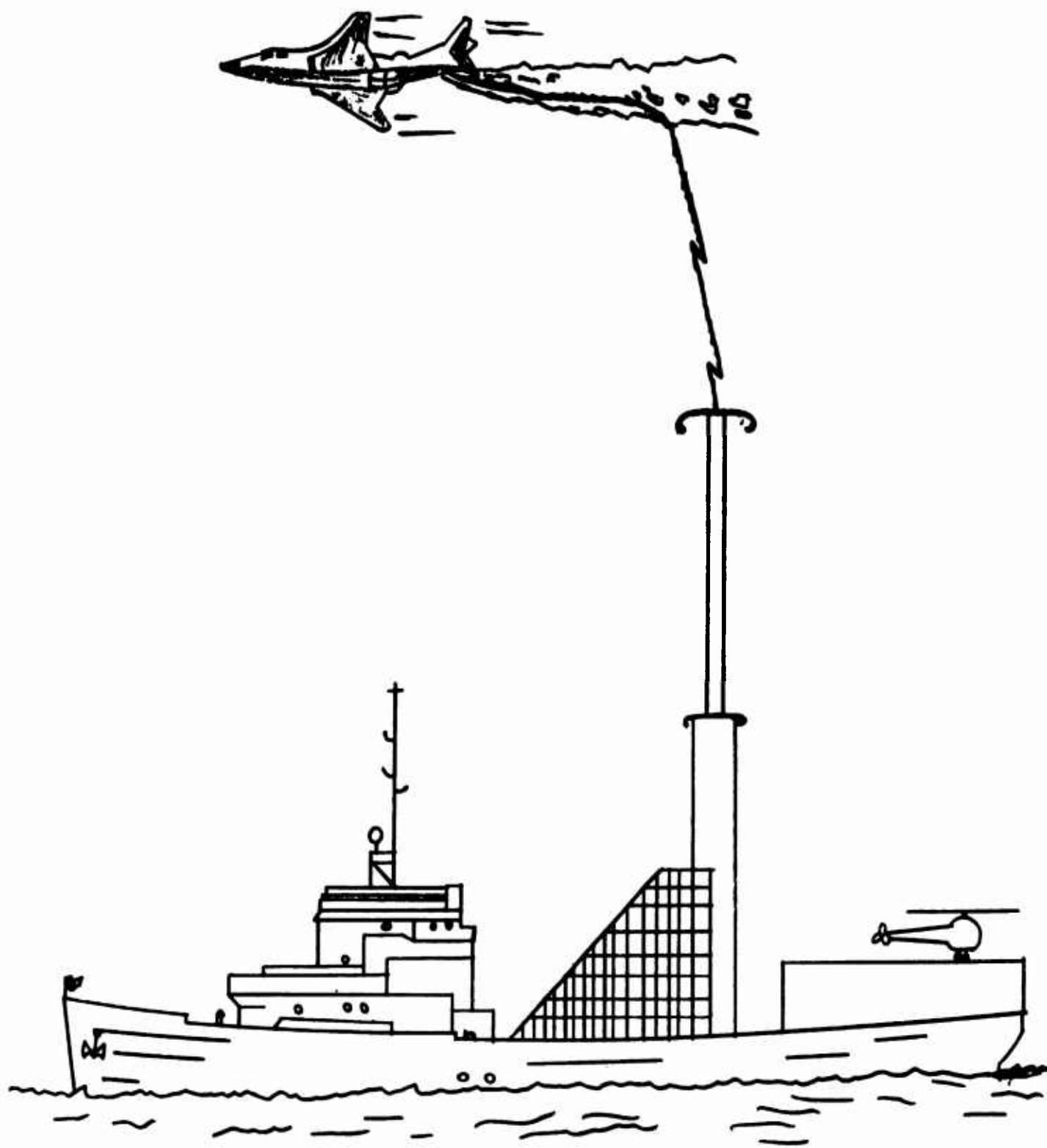


Figure 18. Illustration of possible twenty million oscillatory crest voltage generator in an ocean-going salvage type ship about 200 feet long. The upper two sections telescope and fold down for bad weather or moving. Remote controlled airplane could be checked full scale while in flight with respect to researches on possibly needed lightning protection of fuel system vents from discharge streamer fuel vapor ignition.

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Aircraft flying in thunderstorms may have radio communications disrupted by corona interference from the strong fields present and structural damage may result from direct lightning strokes. Although this short duration interference is not usually a major problem, some interference reduction techniques are possible.

Over 700 incidents of lightning damage to aircraft are tabulated and although the data on jet aircraft is not yet very extensive, the greatest incidence

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